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What can we learn from the measurement $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$? *

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Abstract

We examine the effect of new physics on the $R_b \equiv \Gamma(Z \to \bar{b}b)/\Gamma(Z \to \text{hadrons})$. Conditions for large contributions are derived.

1. Introduction

The SM is generally in excellent agreement with experiment, recent results on the left-right asymmetry A_{LR} at SLC [1] and $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ measured at LEP [2] indicate a possible disagreement at the 2 to 2.5 σ level.

It has been shown in the SM that the $Z - b - \bar{b}$ vertex receives an important contribution from heavy top-quark loops [3], leading us to speculate if new physics may also play a role. The ratio R_b is a clean test for probing the direct contribution from new physics. The reasons are that the ratio is insensitive to QCD corrections as well as the oblique corrections. R_b is measured to be 0.2192 ± 0.0018 [2], which disagrees with the theoretical value 0.215 for $m_t = 175$ GeV predicted by the SM. In this talk, I would like to concentrate on new effects on R_b due to the new physics.

2. Direct corrections to R_b

With the inclusion of vertex corrections, the $Z - b - \bar{b}$ couplings will be shifted as $a^f_{L,R} = a^{f,\text{SM}}_{L,R} + \frac{\alpha_*}{4\pi s^2_*}\delta a^f_{L,R}$, where $a^{f,\text{SM}}_{L,R}$ are the usual left- and right-handed couplings and $\delta a^{f,\text{SM}}_{L,R}$ are the vertex corrections which include also the SM top-quark vertex corrections. Therefore, in the linear order, we obtain [4] $R_b \approx 0.2179 - 0.0021\,\delta a^b_L + 0.00038\,\delta a^b_R$, where $R_b = 0.2179$ for $m_t = 0$ GeV. In the SM, $\delta a^b_R = 0$, whereas $\delta a^b_L \sim m_t^2/4M_W^2$ for large m_t. In Fig. 1, we show the 1σ contour of R_b in the δa^b_R–δa^b_L plane [4]. The origin corresponds to the SM with an unphysical $m_t = 0$. Other values of m_t are indicated on the figure, showing how the SM expectation value is moved away from the experimental

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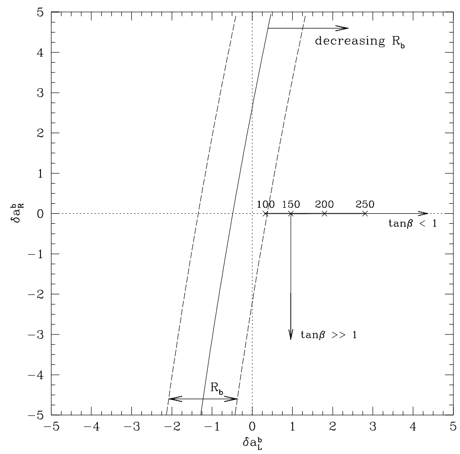

Figure 1: The 1σ contour for R_b in the δa_L^b–δa_R^b plane. The SM predictions with a heavy top are given by the solid line with $\delta a_R^b = 0$. Also included in the figure are the small and large $\tan\beta$ behavior of the vertex corrections in the 2HD model in the case where $m_t = 150$ GeV.

value of R_b. In particular, there is $\sim 2\sigma$ disagreement for $m_t \approx 175$ GeV. In addition, we see that R_b is more sensitive to δa_L than δa_R.

3. New scalars

Assuming new physics mostly couples to the third generation, we consider a single new scalar ϕ with arbitrary isospin(T_3) and electric charge(Q) with the interaction $\mathcal{L}_Y = g\lambda_L \overline{b}_L \phi F_R$+H.c.. The isospins is conserved in the interaction, $T_3(b_L) = T_3(F_R) + T_3(\phi)$. $F_{L,R}$ may transform differently under the SM to accommodate both vector and chiral particles. Thus, we derive

$$\begin{aligned}\delta a_L^b(\phi) &= \lambda_L^2[(T_3(b_L) - Q(b)s_*^2)\Theta - (T_3(\phi) - Q(\phi)s_*^2)(\Theta + \Psi) \\ &\quad +(T_3(F_R) - T_3(F_L))\Delta](M_Z^2; M_\phi^2, m_F^2)\ , \end{aligned} \tag{1}$$

where Θ, Ψ and Σ are finite combinations of Passarino-Veltman functions [5] by

$$\begin{aligned}\Theta(q^2; M^2, m^2) &= q^2[C_{12} + 2C_{22} - C_{23}](0, q^2, 0; M^2, m^2, m^2) \\ \Psi(q^2; M^2, m^2) &= q^2[2C_{22} - C_{23}](0, q^2, 0; m^2, M^2, M^2) \\ .\Delta(q^2; M^2, m^2) &= m^2 C_0(0, q^2, 0; M^2, m^2, m^2)\ . \end{aligned} \tag{2}$$

Θ and Ψ vanish for $q^2 \to 0$. This is a consequence of the vector Ward identity. Δ is non-vanishing in this limit. Expanding Δ in the limit of $q^2 \ll (m^2,\ M^2)$ we obtain. $\Delta_0(x) = \frac{x}{1-x} + \frac{x}{(1-x)^2}\log x$, where $x \equiv m^2/M^2$. In this limit, Θ and Ψ are suppressed by a factor of q^2/M_ϕ^2. Therefore, to the lowest order, we obtain $\delta a_L^b(\phi) = \lambda_L^2(T_3(F_R) - T_3(F_L))\Delta_0(m_F^2/M_\phi^2)$. Firstly, this expression vanishes if F_L and F_R carry the same isospin. This is due to the vector Ward identity.

Therefore, a chiral fermion in the loop are necessary for a large shift in δa_L^b (and hence R_b). Secondly, Δ_0 vanishes in the limit $m_F \ll M_\Phi$. Therefore, the fermion has to be heavier than the boson. We also find that $-1 < \Delta_0(x) \leq 0$ for all x. Thus, the sign of $\delta a_L^b(\phi)$ (or R_b) is determined by the isospins of F. For a scalar χ with the interaction $\mathcal{L}_Y = g\lambda_R \overline{b}_R \chi F_L + \text{H.c.}$, δa_R^b can be obtained from (1) by $(L \leftrightarrow R)$.

In the two Higgs doublet(2HD) model, χ is the same scalar as ϕ which is identified as the charged Higgs H^+. $\delta a_{L,R}^b(H^+)$ can be calculated with $\lambda_L = m_t \cot\beta/\sqrt{2}M_W$ and $\lambda_R = m_b \tan\beta/\sqrt{2}M_W$. In Fig. 1, we have shown how δa_L^b and δa_R^b are shifted in the 2HD model relative to the SM with $m_t = 150$ GeV. Note that, the prediction for R_b from the charged Higgs is always decreased compared to the SM.

4. New gauge bosons

Now, we consider the vertex corrections from new gauge bosons with left- or right-handed coupling, V_L-b_L-$\overline{F_L}$ or V_R-b_R-$\overline{F_R}$, with isospin conservation $T_3(b_L) = T_3(F_L) + T_3(V_L)$ or $T_3(F_R) + T_3(V_R) = 0$ respectively. For $W = V_L$ and $F = t$, the SM result can be reproduced. The vertex corrections are calculated to be

$$\begin{aligned}\delta a_L^b(V_L) \;\; = \;\; & [(T_3(b_L) - Q(b)s_*^2)\tfrac{1}{2}\Phi + (T_3(V_L) - Q(V_L)s_*^2)[B_0(0; M_{V_L}^2, M_{V_L}^2) - \tfrac{1}{2}(\Phi + \Lambda)] \\ & + (T_3(F_R) - T_3(F_L))\Xi](M_Z^2; M_{V_L}^2, m_F^2) \ , \end{aligned} \tag{3}$$

whereas $\delta a_R^b(V_R)$ can be obtained by $(L \leftarrow R)$. Φ, Λ and Ξ are given by

$$\begin{aligned}\tfrac{1}{2}\Phi(q^2; M^2, m^2) &= (1 + \tfrac{x}{2})\Theta(q^2; M^2, m^2) - q^2[C_0 + C_{11}](0, q^2, 0; M^2, m^2, m^2) \\ \tfrac{1}{2}\Lambda(q^2; M^2, m^2) &= (1 + \tfrac{x}{2})\Psi(q^2; M^2, m^2) + q^2 C_{11}(0, q^2, 0; m^2, M^2, M^2) \\ &\quad - [B_0(q^2; M^2, M^2) - B_0(0; M^2, M^2)] \\ \Xi(q^2; M^2, m^2) &= 2m^2 C_0(0, q^2, 0; m^2, M^2, M^2) - m^2 C_0(0, q^2, 0; M^2, m^2, m^2) \\ &\quad + \tfrac{x}{2}[\Theta + \Psi + \Delta](q^2; M^2, m^2) \ , \end{aligned} \tag{4}$$

with $x = m^2/M^2$. We note that the vertex is finite except for the universal piece arising from $B_0(0; M_V^2, M_V^2)$ which can be removed by a proper renormalization [6,7]. Again, Φ and Λ vanish as $q^2 \to 0$, exhibiting the vector Ward identity. In the limit of $q^2 \ll M_V^2$, we obtain $\Xi_0(x) = \frac{x(-6+x)}{2(1-x)} - \frac{x(2+3x)}{2(1-x)^2}\log x$. Note that $\Xi_0(x) < 0$ for $x \leq 0.1$ and $\Xi_0(x) \sim -x/2$ for large x. Therefore, the vertex corrections to the lowest order is given by $\delta a_L^b(V_{L,R}) = \pm(T_3(F_R) - T_3(F_L))\Xi_0(m_F^2/M_{V_{L,R}}^2)$. As in the scalar case, in order to have a large vertex correction, F needs to be chiral and heavier than the gauge boson. The direction of shift is again determined by the isospins of F at least for a heavy F. For the SM, we take $F = t$, leading to $\delta a_L^b(W) \sim x/4$.

5. Conclusion

In this talk, I have discussed the effects of both new scalars and new gauge

bosons on the vertex corrections in a model-independent approach. Two conditions for large vertex corrections are: fermion in the vertex loop must be chiral and it must be heavier than the boson in the loop. We also find that the direction for the corrections is determined by the isospins of the fermion in the loop.

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